A Climatological Analysis of the Köppen Dfa/Dfb Boundary in Eastern North America, 1901-1990[1]

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ABSTRACT. **In 1952, Jack Villmow proposed a new and more northerly border for the Dfa/Dfb climate boundary in eastern North America. This paper follows from Villmow's work with an improved data set over a longer period and considers the issue of anthropogenically induced global warming as a possible cause for explaining any change in the boundary.**

Data were obtained from the Global Historical Climatology Network's *Long-Term Monthly Temperature, Precipitation, Sea Level Pressure, and Station Pressure Data.* Analysis included extracting the annual maximum mean monthly temperature values for 160 weather observing stations in the United States and Canada and mapping the 22° C isotherm (Dfa/Dfb boundary) for three 30-year sequential climatological periods beginning with 1901-1930. Although the Dfa/Dfb boundary did vary latitudinally in each 30-year period, no evidence of warming was found in the north central and northeastern US, or the southern peninsula of Ontario over the 90-year period, particularly in the most recent 30-year comparison (1961-1990).

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INTRODUCTION

This paper cartographically examines changes in the Köppen Dfa/Dfb boundary in eastern North America using three 30-year data sets that correspond to the climatological "normal" as defined by the World Meteorological Organization (WMO 1992). The study begins with 1901-1930 and ends with 1961-1990. During each period, the Dfa/Dfb boundary was mapped. Essentially, the boundary depicts the 30-year mean average location for the transition zone between these climate subtypes as determined by the 22° C isotherm for the warmest monthly mean. The initial hypothesis was that given the concern over long term anthropogenically induced global warming, the boundary should depict a northward advance in either the Midwest, the Northeast or throughout eastern North America.

Similar studies of eastern North America were done by Kendall (1935) and Villmow (1952). Kendall cartographically examined the annual locations of the Köppen A, B, C, and D climates from 1914 through 1931. Several years later, Villmow used data from 1920-1949 in two sets, comparing 1920-1934 and 1935-1949 to specifically analyze Dfa/Dfb boundary changes. Indeed, Villmow concluded that the 1935-1949 period was warmer than 1920-1934, and advocated revising then existing climate maps to depict the northward shift of the Dfa/Dfb boundary. By using a much longer data set and more sophisticated data analysis techniques, this study seeks to reevaluate Villmow's work and relate it to the possibility of global warming.

Although there is little debate that human activity has contributed to increased concentrations of the major greenhouse gases, especially carbon dioxide, there is a great deal of controversy concerning what effect this will have on earth's climate (Panel on Policy Implications 1992). This chasm came to the fore in 1988 when climate modeler James Hansen (director of NASA's Institute of Space Studies) testified before Congress with a 99% confidence that anthropogenic greenhouse gases were causing global warming and contributing to a drought that was affecting corn and soybean production in the Midwest (Kerr 1989).

This was not the first time that anthropogenically induced warming was cited as a detrimental factor in US corn and soybean production. Earlier, Butzer (1980) predicted that by the middle of the 21st century, the corn belt region would shift northward into regions of poorer soils and drainage, thus significantly reducing crop acreage and average yields. In addition, dust bowl conditions would be common on the Great Plains and irrigation water in the American West would be reduced and unreliable (Butzer 1980). Similar findings were reported by Kaufman (1991) who stated that anthropogenic warming would induce changes in agricultural regions. Rosenzweig and Hillel (1993) and a US EPA study forecasted increased food prices and a significant drop in agricultural exports which would occur under the more extreme climate change scenarios (Smith and Tirpak 1989).

Skeptics of anthropogenic warming are concerned about the limits of the global circulation models (GCMs) and the lack of empirical findings. For example, early GCMs predicted three to five degrees Celsius warming by the year 2050, but as the models improved, the forecasted temperature rise dropped to a range of 1.5 to 2.5 degrees Celsius (Lindzen 1990, Michaels and Stooksbury 1992, Schneider 1993). Moreover, an empirical study of the climatic record of the 48 contiguous United States conducted by the National Oceanic and Atmospheric Administration (NOAA) found "no statistically significant evidence of an overall increase in annual temperature or change in annual precipitation for the contiguous US 1895-1987," even though greenhouse gas additions have gone over half-way to a doubling of CO_2 concentration (Brooks 1989).

The NOAA study was national, but regional change is

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most significant for agricultural production (Strommen 1992). For example, regional warming in one area can be masked by cooling in another (Diaz and Quayle 1980). Thus, returning to the initial hypothesis, if anthropogenically induced global warming has occurred, it should be reflected in Dfa/Dfb boundary shifts in all or parts of eastern North America, particularly during the latter period of 1961-1990. Indeed, the potential agricultural impacts as asserted above place particular importance on the corn belt of the Midwest.

The Köppen Climate Classification System

The Köppen system of climate classification is valid for this study because to a large extent it is based on thermal criteria such as annual and monthly means (Trewartha and Horn 1980). For example, the tropical A climates are based on monthly mean averages of at least 18° C, a temperature that corresponds roughly with the poleward limit of tropical vegetation. The subtropical C and middle latitude D climates are separated by the coldest monthly means of above or below -3° C, respectively. Moreover, since Köppen was a plant geographer, the individual subtypes within major categories are often characterized by the intensity of summer or the growing season. For example, a Dfa climate has at least one month above 22° C while a Dfb climate, though all monthly means are under 22° C, has at least four months above 10° C, with the latter criterion being a significant parameter in maintaining a forest. Only the B climates, which are based on water balance deficiencies, are not predicated on thermal parameters. However, even within this category, a thermal criterion (an annual mean of above or below 18° C) is used to distinguish tropical from midlatitude desert and steppe climates (Hidore and Oliver 1993).

As Oliver (1991, 1994) stated, because of its underlying logic and use of definitive rules, the Köppen method remains "the most widely used of the many climatic grouping systems available." As noted, Kendall (1935) used the Köppen system to depict the direction of interannual climatic change of climates east of the Rocky Mountains. Villmow's use of the Köppen classification in 1952 gave further justification for its use with a longer time period for regional comparisons. Indeed, Oliver (1994) recently used a 95-year data set to delineate variation between the Köppen Cfa and Dfa climates across Illinois and Indiana.

The Dfa/Dfb boundary is determined by exceeding or failing to meet the maximum mean monthly temperature of 22° C (71.6° F) during the peak of the growing season (Eichenlaub 1979). As noted above, the Dfa, or warm-summer subtype of the humid continental climate, is determined by a monthly mean above 22° C. Indeed, this climate type is often referred to as the "corn-belt climate" because a significant portion of the world's corn is grown within this climate (Trewartha 1954). In contrast, the cooler Dfb climate has been referred to as the "spring wheat climate" (Trewartha and Horn 1980). It is also noted for summertime resorts or simply a place to vacation and escape the heat. The upper Midwest, upper New England and upstate New York are examples.

Although precipitation occurs year-round in the Dfa and Dfb climates, it is most prevalent in the summer months in the corn and soybean growing areas of the Midwest. It occurs from the advection of relatively unstable maritime tropical (mT) air reacting to an intensive sensible heat flux and frontal lifting. Corn and soybean growth is favored under these conditions because the peak growing season occurs during the rainy season, yet cloud cover is minimized because of the convective component of storm formation. The existing climate is again significant given concerns over the impact of projected global warming in the Midwest region by Butzer (1980).

Villmow's study used data from 101 weather observation stations in the United States and 20 in Canada for the two consecutive periods of 1920-1934 and 1935-1949. He determined the position of the Dfa/Dfb line for each year, and plotted a mean line indicating the average position of the boundary during each period. These mean boundaries were determined cartographically by averaging the latitudinal positions of each of the Dfa/Dfb lines at several meridians of longitude. For his final map, he averaged the position of each of his 15-year periods into a single new 30-year average boundary position and compared it to the currently used boundary as depicted with a dashed line in Figure 1 (Villmow 1952).

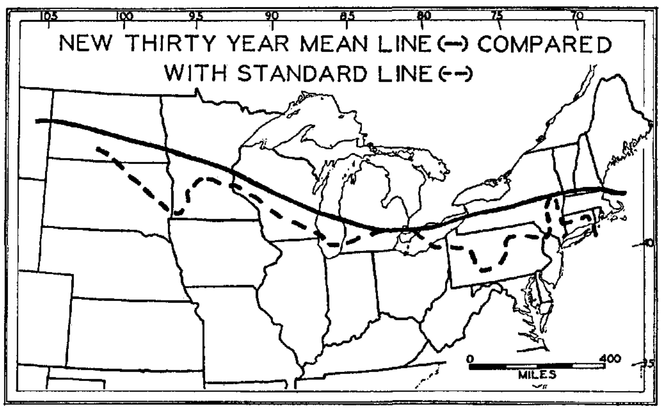

FIGURE 1. Villmow's 1952 placement of Köppen's Dfa/Dfb boundary.

Villmow found that the average position of the Dfa/Dfb boundary for the 30-year (1920-1949) period had indeed changed and in some cases was located as much as 200 miles farther north than the majority of climatic maps indicated. He therefore called for a new Dfa/Dfb boundary to be accepted for the Eastern United States (Fig. 1). A major criticism of Villmow's work centers on his extension of the Dfa/Dfb boundary into the middle latitude steppe (BSk) climate of the Dakotas. Consequently, this study extends no further west than Minnesota.

The 1901-1990 Data Set

For this study, station selection began by replicating as many of the 101 US and 20 Canadian stations used by Villmow (1952) as possible and then adding other stations to improve the spatial resolution. Ultimately, 159 stations were selected. This included slightly over

80 percent of Villmow's original US stations in the Midwest and Northeast. Villmow's stations from the Great Plains were eliminated because of location in the semi-arid BSk climate. To give better boundary conditions for cartographic analysis, the data set was augmented by 43 extra stations from the Dfa/Dfb climates and another six stations chiefly from the adjacent Cfa climate of Missouri and Kentucky (Table 1 and Fig. 2). Eleven

TABLE 1

United States and Canadian weather observation stations.

	CANADIAN STATIONS							
	City	Prov.		City	Prov.		City	Prov.
1	Winnipeg	MNT	4	Windsor	ONT	7	North Bay	ONT
2	Peterborough	ONT	5	Toronto Intl.	ONT	8	Wawa	ONT
3	Welland	ONT	6	Ottawa/Intl.	ONT	9	Montreal	QBC

	UNITED STATES STATIONS							
	City	State		City	State		City	State
10	New Haven	CT	60	Marquette	MI	110	Cooperstown	NY
11	Groton	CT	61	Stambaugh 1S	MI	111	Gloversville	NY
12	Storrs	CT	62	Grand Meadow	MN	112	Indian Lake	NY
13	Des Moines	IA	63	Albert Lea	MN	113	Little Falls	NY
14	Dubuque	IA	64	Zumbrota	MN	114	Saratoga Springs	NY
15	Fayette	IA	65	Fairmont	MN	115	Syracuse	NY
16	Sioux City	IA	66	Milan	MN	116	Oswego	NY
17	Charles City	IA	67	Montevideo	MN	117	Addison	NY
18	Forest City	IA	68	Pipestone	MN	118	Hemlock	NY
19	New Hampton	IA	69	Alexandria	MN	119	Buffalo	NY
20	Algona	IA	70	Minneapolis	MN	120	Rochester	NY
21	Estherville	IA	71	St. Cloud	MN	121	Canton 4SE	NY
22	Fort Dodge	IA	72	Farmington	MN	122	Chazy	NY
23	Rockwell City	IA	73	Maple Plain	MN	123	Cincinnati	OH
24	Storm Lake	IA	74	Mora	MN	124	Columbus	OH
25	Rock Rapids	IA	75	New Ulm	MN	125	Sandusky	OH
26	Charleston	IL	76	Olivia	MN	126	Franklin	OH
27	Chicago (O'Hare)	IL	77	St. Peter	MN	127	Warren	OH
28	Peoria	IL	78	Duluth	MN	128	Toledo	OH
29	Evansville	IN	79	Sandy Lake Dam	MN	129	Harrisburg	PA
30	Anderson Sewage Plant	IN	80	Two Harbors	MN	130	Selinsgrove 2S	PA
31	Fort Wayne	IN	81	Virgina	MN	131	State College	PA
32	Lexington	KY	82	Ada	MN	132	Williamsport	PA
33	Louisville	KY	83	Detroit Lakes	MN	133	Towanda	PA
34	New Bedford	MA	84	Morris WC Exp Stn	MN	134	Reading	PA
35	Taunton	MA	85	Hallock	MN	135	Pittsburgh/Greater Pitts	PA
36	Boston	MA	86	Leech Lake Dam	MN	136	Wellsboro	PA
37	Blue Hill Observatory	MA	87	Park Rapids	MN	137	Erie WSO	PA
38	Bedford	MA	88	Pine River Dam	MN	138	Providence	RI
39	Framingham	MA	89	Pokegama Dam	MN	139	Block Island	RI
40	Portland	ME	90	Roseau 1E	MN	140	Washington DC	VA
41	Lewiston	ME	91	Winnibigoshish Dam	MN	141	Chelsa	VT
42	Orono	ME	92	St. Louis	MO	142	St. Johnsbury	VT
43	Gardiner	ME	93	Springfield	MO	143	Enosburg Falls	VT
44	Houlton	ME	94	Columbia	MO	144	Burlington	VT
45	Millinocket	ME	95	Kansas City	MO	145	Cornwall	VT
46	Detroit	MI	96	Hanover	NH	146	Racine	WI
47	Grand Rapids	MI	97	Concord	NH	147	Madison	WI
48	Kalamazoo State Hospital	MI	98	Atlantic City State Marina	NJ	148	Hancock Exp. Farm	WI
49	Grand Haven	MI	99	Boonton	NJ	149	Portage	WI
50	Big Rapids Waterworks	MI	100	Charlotteburg	NJ	150	LaCrosse	WI
51	Lansing	MI	101	New Brunswick	NJ	151	Green Bay	WI
52	Alma	MI	102	Belvidere	NJ	152	Antigo 1SSW	WI
53	Midland	MI	103	Mohonk Lake	NY	153	Fond Du Lac	WI
54	Owosso Wastewater Plant	MI	104	Port Jarvis	NY	154	Manitowoc	WI
55	Alpena	MI	105	Binghamton	NY	155	New London	WI
56	East Tawas	MI	106	Cortland	NY	156	Ashland Exp. Farm	WI
57	Sault Ste. Marie	MI	107	Ithaca (Cornell Univ.)	NY	157	Medford	WI
58	Cheboygan	MI	108	Oneonta State Univ.	NY	158	Minocqua Dam	WI
59	Ironwood	MI	109	Albany	NY	159	Spooner Exp. Farm	WI

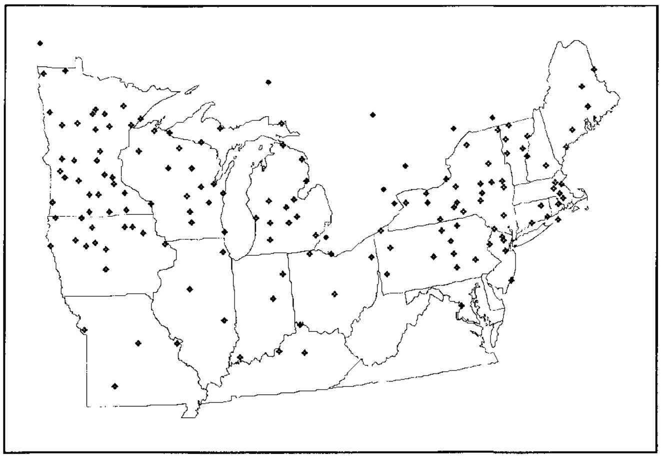

FIGURE 2. Spatial distribution of weather observation stations.

of Villmow's Canadian stations were dropped because of their extreme peripheral location relative to the Dfa/Dfb boundary.

Most of the data were obtained from the Global Historical Climatology Network's *Long-Term Monthly Temperature, Precipitation, Sea Level Pressure, and Station Pressure Data.* The Global Historical Climatology Network (GHCN) project is operated as a joint venture by the Carbon Dioxide Information Analysis Center (CDIAC) and the National Climatic Data Center (NCDC). Their purpose was to compile an improved global data set of long-term monthly mean temperature, precipitation, sea level pressure and station pressure by consolidating the numerous pre-existing national, regional, and global-scale data sets into a single global climate database (Vose et. al. 1992). In doing this, the GHCN data were initially screened for extreme value, then plotted and visually inspected for gross data processing errors and discontinuities, thus making it one of the more reliable data sets available (Vose et. al. 1992).

Nonetheless, the station data selected did have some shortcomings. There was an inconsistency in numeric rounding of the temperature data which in most cases was archived to the nearest tenth of a degree Celsius. However, about 15 percent of the values were from stations that rounded to the nearest whole degree. This was further complicated with some stations having both rounding practices in their record. The GHCN database did not contain documentation on these variations in precision.

It was also possible that precision errors existed as a result of some data values being converted from English to Metric units. If a station's data were recorded in degrees Fahrenheit and rounded to the nearest whole degree, there will be a certain amount of error when it is converted to tenths of a degree Celsius. Again, the GHCN data base does not contain documentation on the details of data conversions.

Finally, there were some data that were inevitably missing, and some of the temperature data simply ended anywhere from 1987 to 1990. Thus, it was necessary to obtain data from two additional sources to complete the data set through 1990. Data for US stations were obtained from the National Climatic Data Center's (NCDC) *Climatological Data* publication and data for Canadian stations were obtained from the World Meteorological Organization's (WMO) *Monthly Climatic Data for the World* (MCDW). Despite these efforts, 2.27% of the data remained missing.

The missing values were compiled in one of two methods. If three consecutive years or less were missing and there was a value preceding and immediately after the missing data, those two values (on either side of the missing ones) were averaged and replaced the missing values. The assumption was that the missing value would more closely reflect the years immediately adjacent. This method was in keeping with the principle of using short term means in near-term forecasting (Lamb and Changnon 1981) and was used on 50% of the missing data cases. If more than three consecutive years were missing or values did not exist on both sides of the missing values, the station's grand mean was used as the replacement figure.

The data for all stations were then divided into three 30-year periods (1901-1930, 1931-1960, and 1961-1990) and the mean position of the 22° C isotherm for the warmest month was mapped onto an Albers Equal Area base map because its standard parallels at 29.5°N and 45°N greatly reduced aerial distortion (Dent 1996). The stations which served as control points were placed computer-graphically onto the maps to within one hundredth of a degree of latitude and longitude by using Atlas Pro.

The placement of the 22° C isotherm was calculated by linear interpolation between the control points (weather stations) for each of the three periods by using the following equation

$$Pd = (\Delta Tt/\Delta T) * d$$

Where Pd is the proportional distance; ΔTt is the difference in absolute value between one of the stations and 22° C; ΔT is the difference in absolute value between two stations bisected by the 22° C isotherm; and d is the distance between the two stations. This method was not only used when stations were nearly across from each other, but also in diagonal or triangular manner to enhance the locational precision of the 22° C isotherm.

This method assumed a uniform or linear gradient, which reinforced the need to augment Villmow's 121 station data set. In reality, such a gradient was not exactly the case, especially in the northeastern US where the Appalachian Mountains exist, but given the scale of this study and the low elevations of the Appalachians in the Dfa/Dfb boundary zone, this method appears reasonably precise. Moreover, since it was used throughout all the maps, any resulting error would likely occur randomly and on a small spatial scale (Hsu and Robinson 1970).

RESULTS AND DISCUSSION

The 1901-1930 average position of the Dfa/Dfb boundary was the most southerly of the three time periods examined (Figs. 3 and 4). Idso (1988) suggests that this

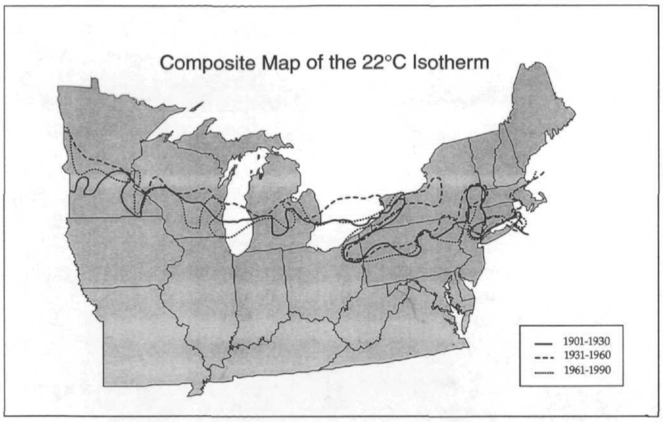

FIGURE 3. Composite of the 22° C isotherm 1901-1930, 1931-1960, and 1961-1990.

was most likely the result of its temporal proximity to the closing of the Little Ice Age (Idso 1988). The 1931-1960 average appears to be the most northerly (Figs. 3 and 5). This period encompassed the "Dust-Bowl" years which were known to be unusually warm and dry. Worster (1979) noted that all US States except for Vermont and Maine experienced drought periods between 1930 and 1936. There is also the suggestion that temperature lags associated with large scale industrialization, motorized transportation, and electrification of the US and Canada may have contributed to the pattern.

The average position for the 1961-1990 period fell approximately midway between the two other boundary positions (Figs. 3 and 6). This suggests that increasing summertime warming, as measured by the warmest monthly mean on a regional scale, was not occurring. If anything, it suggests that a slight cooling trend had occurred when compared to the previous "climatological normal" period.

This could be significant because a warming trend attributable to anthropogenic emissions of CO_2 should have been visible because of the substantial increase in total emissions and the lag (if any) from previous industrial development. Indeed, global warming skeptics

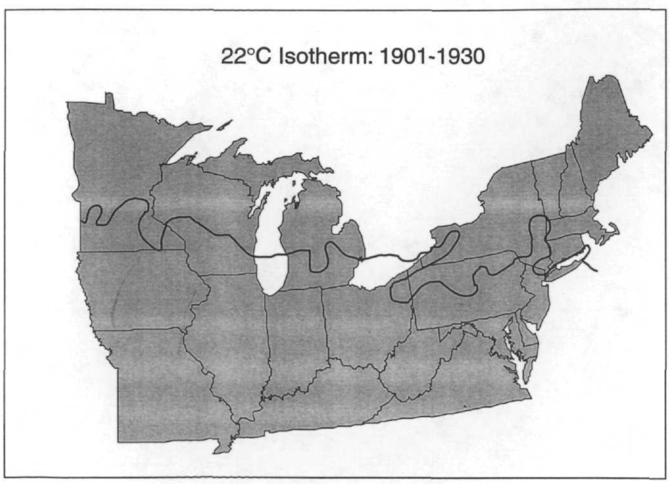

FIGURE 4. The 22° C isotherm 1901-1930.

often state that most of the warming trend during the 100 years prior to 1990 had occurred by 1940, well before the contemporary rise in CO_2 emissions.

The general pattern or configuration for each the Dfa/Dfb boundaries remained largely the same, although latitudinal displacements of the entire line were evident. In some cases, shifts of the 22° C isotherm were more than 300 km, as in western Minnesota. However, this latter variation occurred along the western periphery of the Dfa/b climate where it merges into the drier and more continental BSk climate of the Great Plains.

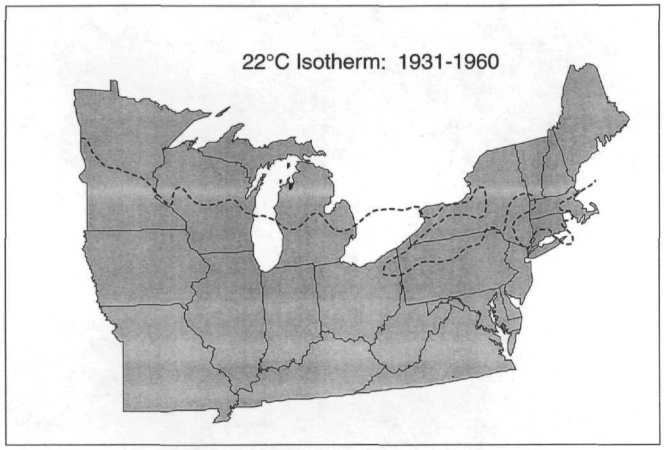

FIGURE 5. The 22° C isotherm 1931-1960.

In the eastern portion of the study area, a series of relatively sharp northward and southward extensions with a topographic explanation was consistently manifested. Southerly extensions into northern Pennsylvania and southern New England were the result of stations being at higher and cooler locations in the Appalachian Mountains, and a northward extension of the boundary in eastern New York State was most likely the result of stations being located within the Hudson River Valley. These stations are at lower and warmer locations. Finally, another northward extension along the coast of Massachusetts and Rhode Island was caused by the moderating effects of the Atlantic Ocean.

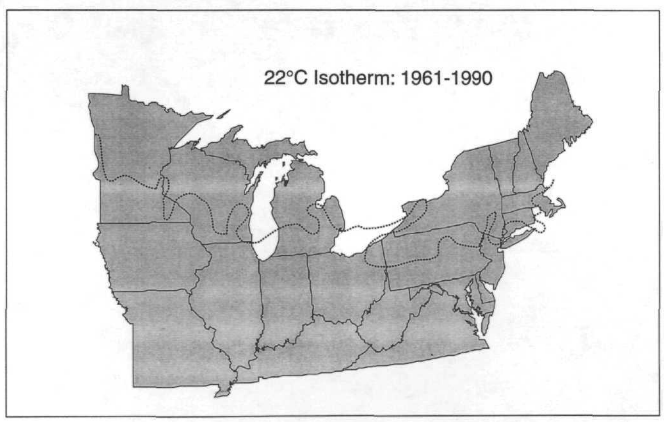

FIGURE 6. The 22° C isotherm 1961-1990.

CONCLUSIONS

This study concludes that (a) use of the Köppen method and its subtypes for tracking latitudinal shifts of the Dfa/Dfb boundary was appropriate given the thermal variables that underpin the method's classification system; and (b) Villmow's previous call for a more northerly border using 1935 to 1949 data occurred in the midst of the warmest 30-year period, 1931-1960. In contrast, the 1961-1990 Dfa/Dfb boundary was between the locations of the 1901-1930 and 1931-1960 borders. Thus far, a warmer summer in the Corn Belt and a consequent shift to the north, as was predicted by Butzer (1980), does not appear to be occurring. Indeed, a slight cooling trend in the summer was noted for 1961-1990.

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